ESTCP
Cost and Performance Report

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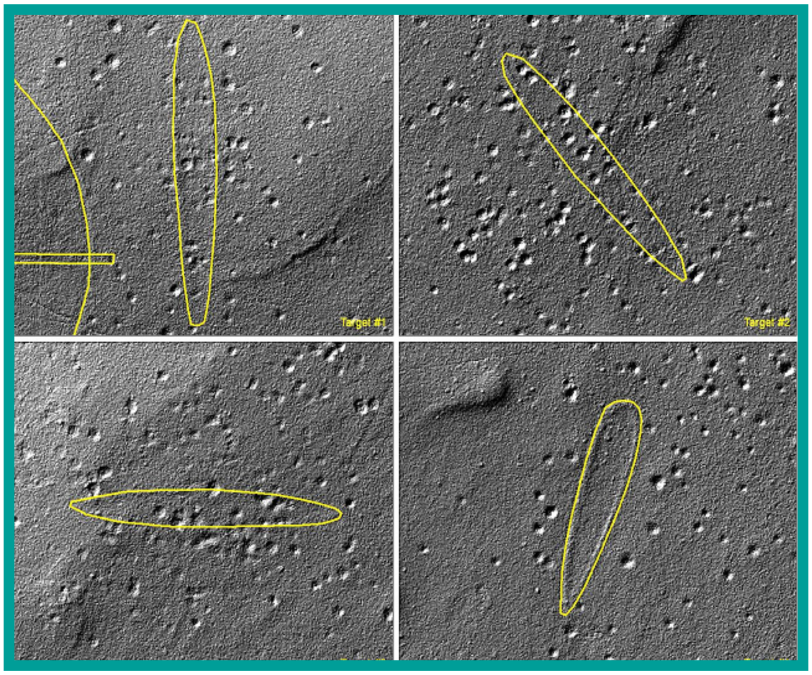

Demonstration of LiDAR and Orthophotography for Wide Area Assessment at Pueblo Precision Bombing Range #2 Colorado and Borrego Military Wash Area, California

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

AGL	Above Ground Level
ASR	Archive Search Report
BT3	Bomb Target 3
BT4	Bomb Target 4
BT64	Bomb Target 64
C208	Cessna 208
CCD	charged coupled device
CERCLA	Comprehensive Environmental, Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CSM	Conceptual Site Model
DEM	digital elevation model
DoD	Department of Defense
DSB	Defense Science Board
DTM	digital terrain model
ESRI	Environmental Systems Research Institute
ESTCP	Environmental Security Technology Certification Program
FLBGR	Former Lowry Bombing and Gunnery Range
FOV	field of view
FUDS	Formerly Used Defense Site(s)
GIS	geographic information systems
GPS	global positioning system
HE	high explosive
HSI	hyperspectral imaging
HVAR	high velocity air rocket
IDL	interactive data language
IMU	inertial measurement unit
ISAT	Image Station Auto Triangulation
LAS	Log ASCII Standard
LiDAR	light detection and ranging
MEC	munitions and explosives of concern
MMRP	Military Munitions Response Program
MNF	minimum noise fraction
MRF	Munitions Related Feature

ACRONYMS AND ABBREVIATIONS (continued)

ND	no detect
PBR	Precision Bombing Range
PDOP	position dilution of precision
POS	Position and Orientation System
RGB	red-green-blue
RMSE	root mean square error
RTK GPS	real-time kinematic GPS
TNT	trinitrotoluene
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
WAA	wide area assessment

ACKNOWLEDGEMENTS

Demonstration of Light Detection and Ranging (LiDAR) and Orthophotography for Wide Area Assessment (WAA) at Pueblo Precision Bombing Range (PBR) #2, Colorado, and Borrego Maneuver Area, California, Cost and Performance Report provides an analysis of the cost of the demonstration and summarizes the performance in terms of the acquisition, processing, analysis, and interpretation of high airborne LiDAR and orthophotography data for WAA at the former Pueblo PBR #2 and at the former Borrego Maneuver Area. The work was performed by Sky Research, Inc. of Oregon, with Dr. John Foley serving as Principal Investigator.

Funding for this project was provided by the Environmental Security Technology Certification Program (ESTCP) Office. This project offered the opportunity to examine advanced airborne methods as part of the Department of Defense's (DoD) efforts to evaluate WAA technologies for efficient characterization and investigation of large DoD sites.

We wish to express our sincere appreciation to Dr. Jeffrey Marqusee, Dr. Anne Andrews, and Ms. Katherine Kaye of ESTCP Office for providing support and funding for this project.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Munitions and explosives of concern (MEC) contamination is a high priority problem for the Department of Defense (DoD). Recent DoD estimates of MEC contamination across approximately 1,400 DoD sites indicate that 10 million acres are suspected of containing MEC. Because many sites are large in size (greater than 10,000 acres), the investigation and remediation of these sites could cost billions of dollars. However, on many of these sites only a small percentage of the site may in fact contain MEC contamination. Therefore, determining applicable technologies to define the contaminated areas requiring further investigation and munitions response actions could provide significant cost savings. Therefore, the Defense Science Board (DSB) has recommended further investigation and use of wide area assessment (WAA) technologies to address the potential these technologies offer in terms of determining the actual extent of MEC contamination on DoD sites (DSB, 2003).

In response to the DSB Task Force report and recent congressional interest, the Environmental Security Technology Certification Program (ESTCP) designed a WAA pilot program that consists of demonstrations at multiple sites to validate the application of a number of recently developed and validated technologies as a comprehensive approach to WAA. These demonstrations of WAA technologies include deployment of high airborne sensors, helicopter-borne magnetometry arrays and ground surveys.

This report describes the cost and performance for the demonstration of the light detection and ranging (LiDAR) and orthophotography high airborne sensor technologies demonstrated at Pueblo Precision Bombing Range (PBR) #2 in Otero County, Colorado, and at Borrego Military Wash in southern California. LiDAR data are critical to the overall WAA process in the creation of an accurate high-resolution bare earth digital elevation model (DEM) for ortho-correction of all other remote-sensing datasets. LiDAR and orthophotography are both valuable for the identification and delineation of possible surface munitions-related features such as target circles and craters associated with munitions use at the site and for development of base mapping layers for site visualization, planning, and analysis.

The objectives of WAA include the rapid and efficient identification of areas of concentrated munitions use through the application of site characterization technologies. Information provided in historical records forms the basis for initial site assessments; field surveys employing a suite of technologies and processing techniques develops the knowledge of these sites and can provide information needed to support decisions at various stages of the munitions response process. Equally as important as defining areas of munitions contamination is the definition of areas with no indication of munitions contamination. The evidence derived from these data analyses assists in prioritizing remediation activities by providing a means for assessing the level of confidence in conclusions about munitions contamination at a site.

1.2 OBJECTIVES OF THE DEMONSTRATION

The LiDAR and orthophotography demonstrations were conducted to determine the utility of these datasets to identify munitions-related features, including target areas, craters, and range infrastructure features; to determine the accuracy of the datasets; and to acquire the datasets for site characterization and planning. For the Pueblo PBR #2 site, specific objectives included confirmation and delineation of the approximate boundaries of two documented bombing targets (Bombing Targets #3 and #4 [BT3 and BT4]) and a suspected 75-mm air-to-ground target area (U.S. Army Corps of Engineers [USACE], 1995). At the Borrego Military Wash demonstration area, the specific objectives included confirmation and delineation of the two targets identified in the Archive Search Report (ASR) (USACE, 1997) and determination of whether evidence exists of any previously unknown target areas.

1.3 REGULATORY DRIVERS

USACE is the lead federal agency under the Formerly Used Defense Site (FUDS) program. USACE administers the FUDS Military Munitions Response Program (MMRP) using DoD investigation/cleanup methods based on the U.S. Environmental Protection Agency (USEPA) Comprehensive Environmental, Response, Compensation, and Liability Act (CERCLA) process.

1.4 STAKEHOLDER/END USER

ESTCP managed the stakeholder issues as part of its WAA pilot program. ESTCP used a process to ensure that the information generated by the high airborne, helicopter, airborne, ground validation surveys was useful to a broad stakeholder community (e.g., technical project managers and federal, state, and local governments, as well as other stakeholders).

1.5 DEMONSTRATION RESULTS

Data collection for the Pueblo PBR #2 demonstration took place in two phases: Phase I in 2004, which covered 2,224 acres within the overall 7,500-acre WAA site, and Phase II in 2005, which covered the remaining 5,276 acres of the study area. For both Phases I and II data collections, the expected spatial accuracies were achieved for both the LiDAR and orthophotography datasets. Upon analysis of the processed datasets, targets, craters, and range infrastructure features were detected. These results achieved the performance objectives outlined in the demonstration plan (Sky Research, 2005a) and are documented in the final report (Sky Research, 2008).

Data collection for the demonstration at the Borrego demonstration site took place in August of 2005. The expected spatial accuracies were comprised due to site restrictions on the emplacement of ground fiducials. Upon analysis of the processed datasets, targets and range infrastructure features were detected and the results compared to ground survey data collected by USACE for validation. The final report documents the demonstration, analysis, and results (Sky Research, 2007a). Although the performance objectives were not all met for the demonstration, the use of LiDAR and orthophotography technologies did confirm the presence of features requiring further investigation and geolocated these features more accurately than had previously been documented. The demonstration showed that erosion and deposition can impact the persistence of detectable features over time; therefore, the potential effect of climactic conditions should be taken into account in assessing site suitability for LiDAR and orthophotography.

Table 1 summarizes the demonstrations and the features detected in the orthophotography and LiDAR datasets.

Table 1. LiDAR and Orthophotography WAA Demonstration Summaries.

Data Collection	Dates	Acres Surveyed	Features Detected
Pueblo PBR #2 Phase I	August 2004	2,224	Bomb target aiming circle, craters, range infrastructure features
Pueblo PBR #2 Phase I	August 2005	5,276	Bomb target aiming circle, ship targets, craters, range infrastructure features
Borrego Military Wash	August 2005	7,940	Bomb target aiming circle, range infrastructure features

Overall, LiDAR and orthophotography technologies are efficient, cost-effective tools for WAA. As the first part of an integrated WAA investigation, the collection of thousands of acres of data per day and the analysis of LiDAR and orthophotography datasets yields results that can be used to characterize the extent of contaminated areas and delineate "clear" areas of large sites. The utilization of these technologies for WAA will result in a reduction in the overall costs of remediation by decreasing the number of acres requiring more extensive munitions response actions and focusing the extent of further investigations, ultimately yielding more efficient use of the DoD's limited cleanup resources.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Airborne sensors utilized for this demonstration are based on existing, well-developed airborne remote sensing technologies. LiDAR is a scanning and ranging laser system capable of producing precise, high-resolution topographic data. The technology has been in existence for more than 20 years, although the commercial application for topographic maps has developed only within the last 7 to 10 years. Orthophoto imagery was first produced more than over 30 years ago and was first created using a combination of optical and digital processing. However, in the early 1990s digital orthophotography became a commercial production reality due primarily to the increased availability of more powerful computers at more affordable prices.

The application of these technologies to characterization of features related to munitions and MEC contamination is relatively recent. DoD has invested significant resources demonstrating the utility of applying WAA technologies, including LiDAR and orthophotography, for the characterization of MEC contamination on large DoD sites, including the WAA pilot program demonstrations. In addition, production level surveys have been conducted on behalf of the USACE at a number of former and active sites.

2.2 TECHNOLOGY DESCRIPTION

The technologies utilized for these demonstrations included a fixed-wing plane platform housing the data acquisition technologies and a suite of data processing and analysis software. The ALTM 3100 LiDAR system, ALTM 4K02 Digital Metric Camera, and the Position and Orientation System (POS) were mounted in the Sky Research Cessna 208 (C208) Caravan aircraft (Figure 1). The C208 is an unpressurized, single-engine, high wing turboprop with fixed landing gear. A removable composite cargo pod provides housing for the equipment and sensors; both the LiDAR and orthophotography sensors were installed to allow for concurrent data collection.

Figure 1. The C208 Fixed-Wing Platform Houses the Orthophotography and LiDAR Sensors for Concurrent Data Collection.

2.2.1 LiDAR Technology

The LiDAR data collection system used for these demonstrations—an Optech ALTM 3100 laser scanner, global positioning system (GPS), and inertial measurement unit (IMU)—is capable of producing precise, high-resolution topographic data. The Optech ALTM 3100 LiDAR sensor specifications are summarized in Table 2.

Table 2. LiDAR Specifications.

Detector type	Optech® LiDAR ALTM 3100
Spacing	30 cm to 5 m spot spacing
Contour interval	Dependent on spot spacing with an approximate 1-m (spacing) to 30.5-cm (contour interval) ratio
Operating altitude	80-3,500 m above ground level (AGL) nominal
Elevation accuracy	<15 cm at 1,200 m; 1 sigma <25 cm at 2,000 m; 1 sigma <35 cm at 3,000 m; 1 sigma
Horizontal accuracy	Better than 1/3,000 x altitude; 1 sigma
Range accuracy	2-3 cm, single shot
Range resolution	1 cm
Measurement rate	33,000 to 100,000 measurements per sec
Scan angle	0 to ± 25°
Swath width	Variable from 0 to 0.93 x altitude
Scan frequency	0-70 Hz, depending on scan angle
Laser classification	Class IV (FDA Code of Federal Regulations [CFR] 21)
Laser repetition rate	33 kHz (max. altitude AGL 3,500 m) 50 kHz (max. altitude AGL 2,500 m) 70 kHz (max. altitude AGL 1,700 m) 100 kHz (max. altitude AGL 1,100 m)
Operating temperature	10-35° C
Humidity	0-95% noncondensing

The laser scanner operates by emitting high-frequency infrared laser beams. The scanner records the time difference between the emission of the laser pulses and the reception of the reflected signal. A mirror mounted in front of the laser rotates, directing the laser pulses to sweep back and forth perpendicular to the flight direction, which allows the laser scanner to collect swaths of topographic data as the aircraft moves forward. The position of the aircraft is determined by processing differential, dual-frequency, kinematic GPS observations. The GPS located in the aircraft is supported by several ground stations that are located within the vicinity of the acquisition area. The IMU determines the orientation of the aircraft (pitch, roll, and yaw) during data collection. By combining the IMU data with the post-processed GPS data, the exact trajectory of each laser pulse is determined during data processing.

During data acquisition flights, the sensor operator observes the real-time LiDAR swath coverage to assure full coverage of the survey area. The operator also monitors in-flight position dilution of precision (PDOP) and GPS satellite coverage. If tolerance thresholds of either are exceeded, data acquisition activities are put on hold until acceptable conditions resume. After the data acquisition flights, data from GPS base stations are checked against in-flight GPS data for concurrence. Once data quality assessments are completed, all data (image and ancillary) are transferred to a centralized location for preprocessing and quality control analysis.

Processing of the raw LiDAR datasets employs a variety of software technologies. Sky Research uses the following technologies:

- POSPac/POSGPS® software for GPS data processing
- POSProc software for combining postprocessed GPS data with IMU data
- Optech's REALM software for initial processing and output of LiDAR point cloud data
- Terrasolid's TerraScan software for classification of LiDAR points into vegetation, ground, and "other," creating bare earth and surface model digital terrain models (DTM)
- Environmental Systems Research Institute's (ESRI) ArcGIS geoprocessing scripts and Natural Neighbor interpolation for interpolating both DTM models to DEMs and shaded relief imagery
- Visual Learning Systems' Feature Analyst ArcGIS extension and custom interactive data language (IDL) software algorithms to locate, detect, and characterize microtopographic features, including craters.

2.2.2 Orthophotography Technology

For these demonstrations, a high-resolution Optech ALTM 4K02 digital metric camera with high-resolution charged couple device (CCD) backing was mounted in the aircraft to capture the aerial photography. The system works as follows: the CCD converts light into electrons, which are enumerated and converted into a digital value. The ability of a CCD to accurately measure and convert the value of electrons into digital format is the measure of quality. As a small format system, the ALTM4K02 camera offers a 36° field of view (FOV), minimizing layback distortion at the edges of images and minimal image distortion during the orthorectification phase of processing. The manufacturer's specifications for the camera used for data collection are summarized in Table 3. The camera is linked to a computer that controls the frequency and length of exposures, resulting in overlapping images. Information collected from the GPS and IMU are used to rectify the aerial photographs. This is accomplished by assigning a geographic coordinate to each image derived from the processing of the GPS data. In addition, distortions created by camera tilt, lens distortion, and terrain displacement are removed to produce an orthophotograph.

Table 3. Camera Specifications.

Detector type	Optech ALTM 4K02 Digital Metric Camera DSS 301 SN0046-55-mm lens
Lens type	Zeiss Distagon
Focal length	55.073 mm
Field of view	36°
CCD specifications	4,092 (along flight) x 4,079 (cross flight) Pixel size of 0.000138 in
Shutter speed	1/125 to 1/4000 sec
Principal point	Xppac (mm) -0.390, Accuracy 0.0036 Yppac 0.222, Accuracy 0.0036 Measured from image center (pixel size = 9 microns)
Pixel non-squareness	1.0, Accuracy 0.0000001
VIS calibrated gain value	0.98
VIS calibrated ISO	300
VIS calibrated exposure compensation	-0.70

During the data acquisition flights, the sensor operator observes the real-time photograph footprint coverage to assure required percentage of overlap for the survey area. The operator observes real-time photo display for verification of image quality. The operator also monitors in-flight PDOP and GPS satellite coverage. If tolerance thresholds of either are exceeded, data acquisition activities are put on hold until acceptable conditions resume. After the data acquisition flights, data from GPS base stations are checked against in-flight GPS data for concurrence. Once data quality assessments are completed, all data (image and ancillary) are transferred to a centralized location for preprocessing and quality control.

Processing the raw data sets employs a variety of software technologies. Sky Research uses the following technologies:

- POSPac/POSGPS® software for GPS data processing
- POSProc software for combining postprocessed GPS data with IMU data
- Raw photographs developed into TIFF format with manufacturer-calibrated true-color (VIS) filter
- DSS MissionView 2.0 for downloading images from removable drives
- POSEO 4.1 for processing the photographs to sync with GPS data
- ZI Imaging Image Station Auto Triangulation (ISAT) software to combine formatted image files with exterior orientation files
- ImageStation OrthoPro software for rectification of the photography to the DTM.

2.2.3 Data Analysis

Once processed, the LiDAR/orthophotography data sets are analyzed to characterize any munitions-related features that are visible in the data sets and that may be useful in characterizing munitions contamination present at the site. These surface features may include high explosive (HE) craters, target and range berms, burial trenches, abandoned service roads, artillery targets, and other features where a surface topographic or soil/vegetation expression is observed in the LiDAR and/or orthophotography data sets. Extraction of the potential munitions-related features from the orthophotography and LiDAR data sets is both an automated and analyst-performed task that combines multiple-overlay image interpretation with automated spatial feature recognition processes utilizing ArcGIS and Visual Learning Systems software.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Component WAA technologies have been developed and tested at a number of defense sites over the past ten years. A WAA at Former Lowry Bombing and Gunnery Range (FLBGR) in Colorado was the first practical application of the use of LiDAR and orthophotography methodology for MEC site assessment. However, at the time the FLBGR WAA was conducted, much of the site had been surface-cleared of munitions contamination at known sites, significantly complicating the analysis. Since then, demonstrations of LiDAR/orthophotography technologies have been conducted at each WAA pilot program demonstration site.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

As with all characterization technologies, site-specific advantages and disadvantages exist that dictate the level of success of their application. However, in general, the advantages of high airborne sensor WAA technologies include:

- the ability to characterize very large areas;
- characterization of the site in terms of munitions-related features, which provides a more robust structure to the overall conceptual site model (CSM);
- ability to deploy multiple sensors; and
- ancillary products, including high fidelity DEMs and high resolution photography that can be used for a wide variety of site activities.

Limitations of the demonstrated WAA technologies include:

- Use of high airborne sensors is not intended to detect individual munitions.
- Site physiography, such as terrain and vegetation, can constrain the use of technology for munitions-related feature detection.
- LiDAR and orthophotography technologies can only detect features with expression on the earth surface.
- Each technology has survey rate and cost versus detection fidelity trade-offs.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Performance objectives are critical demonstration components because they provide the basis for evaluating the technology performance. For these demonstrations, primary and secondary performance objectives were established and documented (Table 4). These objectives include the georeference accuracy of the datasets and the ability to detect surface features indicative of potential MEC contamination, including target areas, craters, and range infrastructure.

3.2 TEST SITE SELECTION

Pueblo PBR #2 was initially selected for demonstration in 2004 based on the site characteristics, which were expected to be amenable to feature detection in high airborne remote sensing data sets. In 2005, ESTCP created the WAA pilot program in response to the DSB Task Force report and congressional interest, to validate the application of a number of recently developed technologies as a comprehensive approach to WAA. The WAA pilot program demonstration sites were selected based on criteria selected by the ESTCP Office in coordination with the WAA Advisory Group. In response to that selection, the demonstration area for Pueblo PBR #2 was expanded and a second data collection (Phase II) was conducted in 2005 to encompass a second documented bombing target and a suspected bombing target. Borrego Military Wash was also selected as a demonstration site at that time.

3.3 TEST SITE HISTORY/CHARACTERISTICS

Pueblo PBR #2 was used as a World War II-era military training facility, located in the southern part of Otero County, Colorado. Within the 105-square-mile (67,770 acres) FUDS, the demonstration area consists of approximately 7,500 acres encompassing the two bombing targets (BT3 and BT4) and the suspected 75-mm air-to-ground target area documented in the ASR (USACE, 1995) and shown in Figure 2. It was postulated prior to the demonstration that undocumented target locations could potentially lie within the study area. Land within the study area is primarily in federal ownership managed by the U.S. Forest Service as the Comanche National Grasslands with portions leased to private owners or owned by the State of Colorado. Somewhat less than 2,000 acres of the 7,500-acre study area are privately owned, nonresidential gazing lands.

The Borrego Military Wash demonstration site was a 7,500-acre subsite of the Borrego Maneuver Area and is representative of a large number of munitions sites associated with the nearby California-Arizona Maneuver Area. The Borrego Maneuver Area encompasses desert, mountains, and badlands, with negligible amounts of arid climate vegetation species. It was acquired by use permit from the State of California in 1942 for use as a force-on-force maneuver area. The Army closed their portion in 1944 but the Navy continued to use their areas through 1953. Training activities at the Borrego Maneuver Area included preparing combat troops for desert warfare, instruction of mechanized artillery service units and staff, antiaircraft training, and practice bombing.

Table 4. Primary and Secondary Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Metric Met?
Qualitative (Primary)	Ease of use and efficiency of operations	Efficiency and ease of use meets design specifications	General observations	Pueblo PBR #2: Met Borrego: Met
Quantitative (Primary)	Georeference position accuracy for each sensor system	LiDAR: Vertical accuracy – 15-cm root mean square error (RMSE); Horizontal accuracy – 40-cm RMSE	Pueblo PBR #2: Comparison of data sets with ground fiducials Borrego: Calculated from average offset for eight corners of two rake stations*	Pueblo PBR #2: Met Borrego: Not Met*
		Orthophotography: Horizontal accuracy – 40-cm RMSE		Pueblo PBR #2: Met Borrego: Not Met*
	Target area detection	>0.90 of target areas having topographic aiming point features	Comparison of ortho and LiDAR data analysis results with ground validation data**	Pueblo PBR #2: Met Borrego: Not Met***
Quantitative (Secondary)	Crater detection	>0.75 (craters <1 m) >0.90 (craters > 1 m)	Comparison of LiDAR data analysis results with ground validation data**	Pueblo PBR #2: <1 m: Not within detection limits; >1 m: Performance met Borrego: No craters detected or located during ground survey
	Range infrastructure detection	>0.90	Comparison of ortho and LiDAR data analysis results with ground validation data**	Pueblo PBR #2: N/A Borrego: Identified features verified as range infrastructure

* Performance confirmation method reported is typically comparison of datasets with ground fiducials; however, for the Borrego demonstration, another confirmation method (as described in Section 4.1.2.2) was used because of restriction on emplacements of fiducials, which also resulted in a lower accuracy than anticipated.

** For the Borrego demonstration, visual site inspection results were utilized for validation purposes.

*** For the Borrego demonstration, five target features were detected and one target feature not detected resulting in a calculated performance value of 0.83.

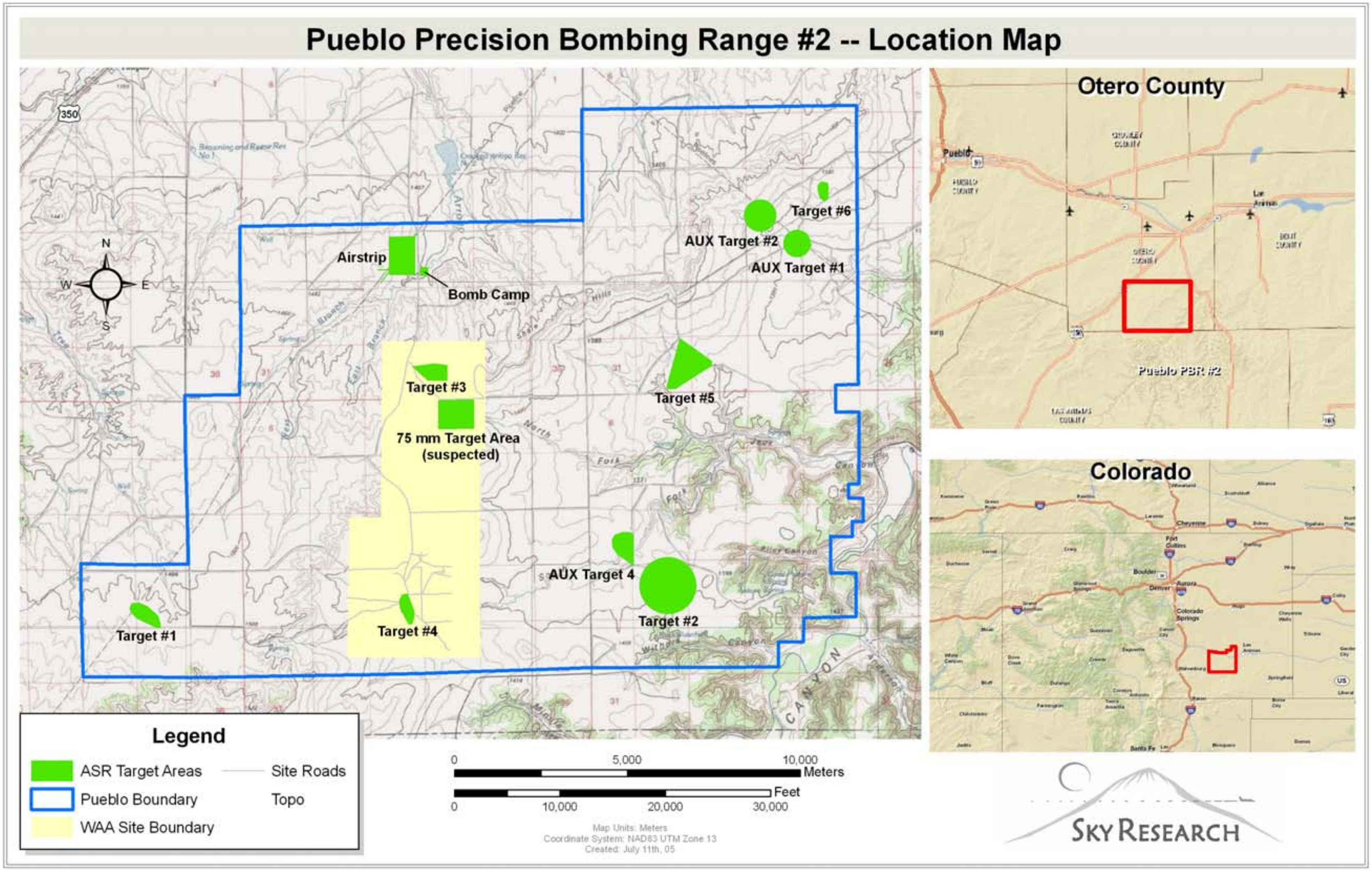

Figure 2. The WAA Demonstration Area (in Yellow) **is Located Within the Former Pueblo PBR #2 in Otero County, Colorado.**

The Borrego Military Wash contains two sub-areas identified in the ASR. The area designated as E-1 contains a variety of targets and munitions-related features, including contained bombing, strafing, and rocket targets with rake (observation) stations that are firing points for 40-mm and 90-mm antiaircraft weapons systems. There also may have been an air-to-ground railway strafing target as well as a bermed area for ground-to-ground firing as part of an Army anti-mechanized target. Sub-area E-2 was designated as a safety buffer area around Sub-area E-1. The Borrego Military Wash 7,940-acre demonstration area was buffered substantially (by 0.5 km) to ensure that all the extents of the project area contained an adequate number of tie points for the orthophotography dataset. Figure 3 shows the Borrego Maneuver Area boundaries, Borrego Military Wash boundaries, and the E-1 and E-2 Sub-area boundaries.

3.4 PHYSICAL SETUP AND OPERATION

3.4.1 LiDAR Calibration

Prior to data collection flights, a calibration flight was completed over a known calibration site located at the Sky Research facility in Ashland, Oregon. This calibration flight served several purposes─to assess the alignment and offsets between the scanning mirror of the sensor, the IMU, and the GPS antenna on the aircraft and to compare the results of the flight with known survey points.

3.4.2 Mobilization/Demobilization

Mobilization and demobilization for these demonstrations required transport of the plane, equipment, pilot, and sensor operators from Ashland, Oregon, to the base of operations. Ground personnel deployed from Denver, Colorado, to establish ground fiducials, establish and operate GPS base stations, and provide logistical support returned to Denver at the conclusion of the demonstrations.

3.4.3 Crater Emplacement

Ten craters were manually created at the Pueblo demonstration site for an assessment of crater detection ability using LiDAR data. The emplaced craters consisted of a controlled series of circular depressions and eight existing HE craters. The ability to detect each crater using the LiDAR imagery was classified into one of four categories─high, medium low, and no detect (ND).

3.4.4 Ground Control

A ground support team operated GPS base stations, collected GPS road calibration transects, placed ground control target panels for the LiDAR and orthophotography data collection, and collected GPS data during the data collection flights.

3.4.5 Navigation Systems

An Applanix 510 A/V POS system was co-mounted with both sensors to record the aircraft's GPS position utilizing a dual frequency GPS receiver and attitude (pitch, roll, and yaw) utilizing an IMU. The Optech ALTM-NAV software package was used for flight navigation and allowed

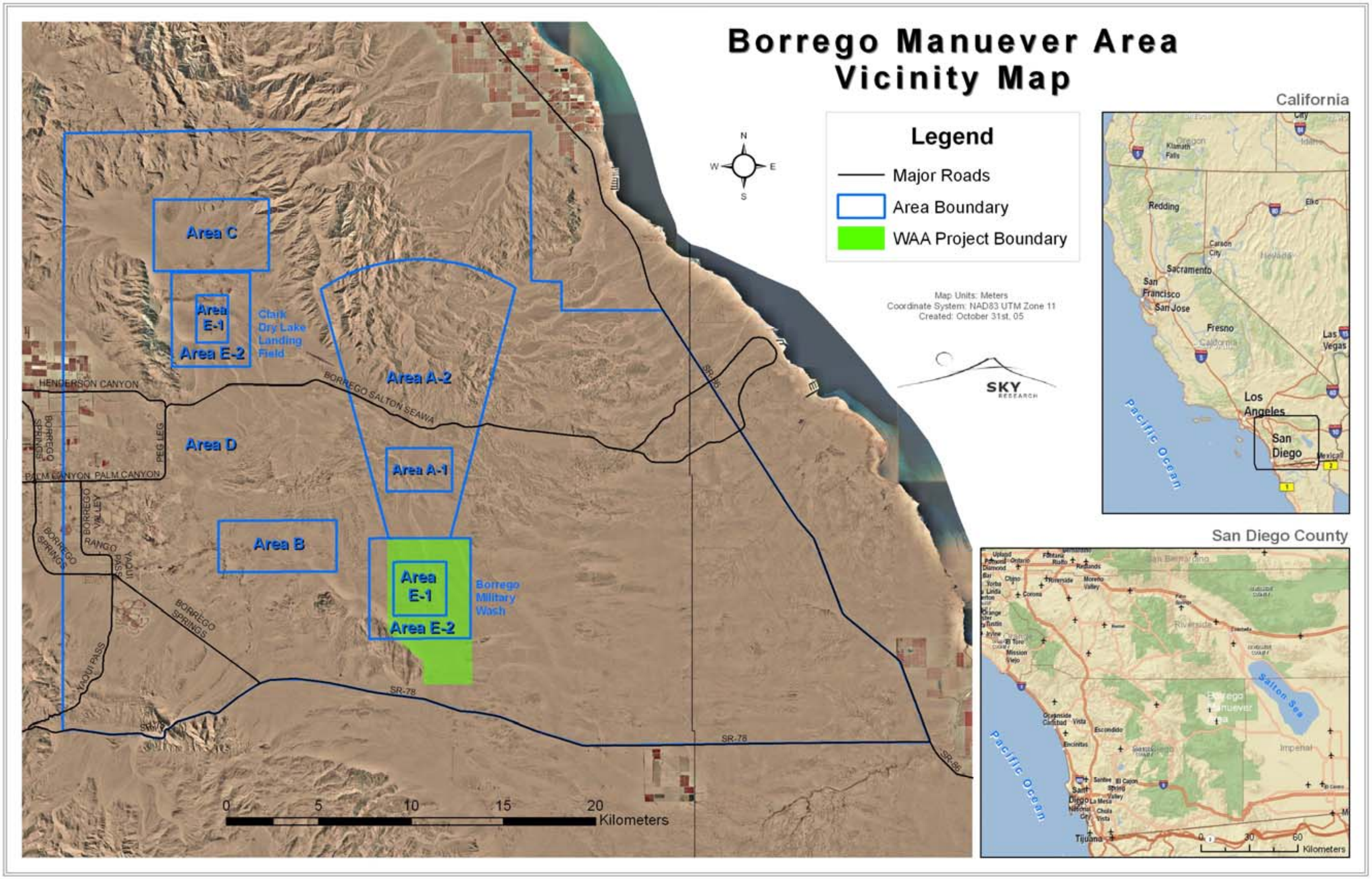

Figure 3. The WAA Demonstration Was Conducted in Sub-Areas E-1 and E-2 of the Borrego Military Wash of the Borrego Maneuver Area.

the sensor operator to view in real time the swath of the laser system, images, PDOP levels, and number of satellites, as well as any problems with the laser or camera system.

3.4.6 Period of Operation

The Phase I data collection flights at Pueblo PBR #2 occurred on August 20 and 23, 2004. A total of 5 hours of flight time was needed to collect data over approximately 6,700 acres. Phase II data collection occurred on August 6, 2005, in one 3.5-hour flight over approximately 6,600 acres. The Borrego data collection occurred on August 16, 2005. One flight lasting 3.6 hours was needed to collect data over approximately 8,900 acres (note, the 8,900 acres of survey data includes substantial buffering to ensure sufficient data collection).

3.5 OPERATING PARAMETERS FOR THE TECHNOLOGY

The flight parameters for the data acquisition surveys were set during the planning stages to meet the required accuracies for the LiDAR and orthophotography data sets at flight altitudes 800 m of AGL and flight speeds of 54 m/sec (105 knots). Flight-line spacings were approximately 230 m to allow 50% overlaps with the 560-m swath widths achievable at 800 m for LiDAR data acquisition. Average elevation sample postings were planned for less than 40 cm, with planned vertical accuracy of 15 cm and horizontal accuracy of 40-cm RMSE. At the planned collection parameters, vertical accuracies relative to adjacent sample points were predicted to be better than 5-cm RMSE, providing very high resolution surface modeling capabilities. Orthophotography data were collected concurrently with the LiDAR data collection and collected on every other LiDAR flight line, with cross-track overlaps of 36% and along-track overlaps of 30%. Tables 5 and 6 summarize the operating parameters for the data collections.

Table 5. Acquisition Parameters for LiDAR Data Collection.

Measurements per second	100,000
Scan width	370 m
Scan overlap	50% (185 m)
Scan frequency	60 Hz
Scan angle	+/- 13
Spot spacing	0.44 m

Table 6. Acquisition Parameters for Color Orthophotography Data Collection.

Field of view	36°
Imaging swath/photo coverage	36% cross-track overlap; 30% along-track overlap
Ortho-rectified pixel size, resampled	0.16 m/pixel

3.6 ANALYTICAL PROCEDURES

LiDAR processing transforms raw binary data into a functional DEM. Primary processing of raw digital camera data results in a seamless, orthometrically correct 24-bit red-green-blue (RGB) aerial photomap of the site. Secondary analyses included conversion of processed sensor datasets into suspected munitions-related feature datasets utilizing a variety of processing and analytical techniques. Several image processing steps were used to generate derivative raster datasets that enhance feature detection, followed by a systematic manual inspection and interpretation of the imagery in a geographic information systems (GIS) workstation environment that facilitates multiple image overlays with transparency and edge-sweep controls, contrast stretching, multiple-band blending in an RGB color model, and other visualization tools. Interpreted image features were incorporated into the site geodatabase as vector point and polygon map features.

3.6.1 Computation of Derivative LiDAR Images and Analysis Grids

The LiDAR bare earth DEM was used to compute two different derivative images, including a “hillshade” image and an “analytic” image. The hillshade was computed using a raster analysis function that computes the hypothetical illumination of a surface by determining illumination values on a cell-by-cell basis for each cell in the image. The analytic image was a high-pass filter of the bare earth DEM computed by subtracting the elevation value of each DEM cell from the average of the surrounding cells in a defined circular neighborhood. This process resulted in an image that emphasizes microtopographic features in the image of a scale correlated with the filter’s search radius. To enable an efficient and systematic analysis, the study area was subdivided into 100-m grid cells and further subdivided into 20-m cells. This two-tiered grid system was used by the analyst to track progress and ensure complete and even review of the imagery.

3.6.2 Target Feature Identification and Extraction

Datasets within each grid cell were systematically examined in ArcGIS for target features, including circles, “cross-hair” aiming points, ship outlines, and rectangular shapes that could represent airstrips, buildings, or other target types. As features were identified in an image and corroborated in other imagery, outlines were digitized by the operator into a feature-class geodatabase layer and assigned attributes such as area, centroid, primary and corroborating sensors, description, and feature type.

3.6.3 Crater Feature Identification and Extraction

Crater feature identification and extraction utilized the LiDAR-derived hillshade and analytic high-pass DEM images. For purposes of a crater detection analysis, HE impact craters were defined as circular or semicircular depressions of any size up to 20 m in diameter. Perimeter circularity, concave bottom profile and raised rim were considered to be diagnostic attributes. To classify a depression as a crater, any significant irregularity of shape (departure from circularity) should be explained by adjacent crater features, rock outcrops, or recent disturbance. An automated circular depression detection algorithm using the Feature Analyst extension for ArcGIS combined with a custom radial search pattern was used for detecting craters, which were later manually verified or rejected using the LiDAR hillshade and analytic images. Verified craters were digitized; overlapping craters were digitized as overlapping circles. After the craters were digitized for each analysis grid, the operator ran a custom spatial analysis script within the ArcGIS environment that extracted the high and low elevations within each circle from the underlying DEM, and stored these elevations and the difference (crater depth) as attributes for each. Crater area, perimeter length, and centroid coordinates were also saved as feature attributes.

To visualize the distribution of craters across the study area, a density analysis was performed by computing a kernel density raster whose cell values each describe the crater density in craters per hectare of a circular neighborhood around each cell. Changes in the neighborhood radius affect the resulting density surface, with larger radii producing a more generalized density model and smaller radii producing more detail. Therefore, a neighborhood radius appropriate to the crater density and patterns was interactively determined to produce a density surface most appropriate to the distribution of craters across the study area landscape.

3.6.4 Range Infrastructure Identification and Extraction

The LiDAR and orthophoto data sets were analyzed to extract other anthropogenic features to aid interpretation and characterization of the MEC contamination patterns by the spatial correlation of extracted features such as transport routes and evidence of excavation activities with documentary site usage information. The feature extraction methodology used to extract infrastructure features was essentially the same as that described for the identification and extraction of target features and was conducted concurrently with that extraction.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

4.1.1 Crater Detection Analysis

The crater detection analysis completed as part of the Pueblo PBR #2 demonstration showed that LiDAR imagery can detect HE craters at a crater diameter threshold of about 150 cm and a diagnostic crater diameter threshold (i.e., terrain depression can be recognized as a probable HE crater) of about 350 cm. Both the hillshade and analytic high-pass imagery were evaluated for crater detection; the analytic image was found to be more useful because of the improved detectability of the characteristic raised berm of excavated soil around the perimeter of the craters and the improved contrast of even small circular depressions with surrounding terrain. Table 7 shows the results of the analysis and includes the detection classification (i.e., high, medium, low, ND) for both the LiDAR derived hillshade and analytic high pass imagery types and the estimated diameter and depth.

Table 7. Diagnostic Detectability of Crater Features in LiDAR Imagery.

Crater ID	Hillshade	Analytic	Diameter (cm)	Depth (cm)
17	High	High	1121	90
15	High	High	564	50
16	High	High	534	37
19	High	High	501	36
13	High	High	399	31
14	Medium	High	353	24
20	Low	Medium	288	14
18	Low	Medium	194	12
1	Low	Medium	177	30
3	Low	Low	166	30
7	ND	Low	104	28
12	ND	ND	74	13
2	ND	ND	74	11
10	ND	ND	65	24
5	ND	ND	63	25
11	ND	ND	54	28
9	ND	ND	46	20
8	ND	ND	45	20

4.1.2 Spatial Accuracy

4.1.2.1 Pueblo PBR #2

The LiDAR and orthophotography spatial accuracy performance goals were met for the Pueblo PBR #2 demonstrations. To determine LiDAR spatial accuracy, horizontal offsets were calculated by determining the centroid of the modeled perimeter versus surveyed center point.

Vertical offsets were calculated from average feature surface elevation versus surveyed center point elevation. To determine orthophotography spatial accuracy, image coordinates of ground targets were compared to GPS position, and X-Y offsets were calculated. Accuracy results are provided in Tables 8 and 9.

Table 8. LiDAR Data Accuracy Results at Pueblo PBR #2.

Accuracy Metrics	Phase I Data (cm)	Phase II Data (cm)
Y RMSE	7.0	9.2
Y linear error (95% confidence level)	13.7	18.1
X RMSE	27.4	7.6
X linear error (95% confidence level)	53.7	15.2
RMSE horizontal radial error (68.3% confidence level)	28.2	8.5
Horizontal radial error (95% confidence level)	42.1	16.6
RMSE vertical linear error (68.3% confidence level)	11.1	3.2
Vertical linear error (95% confidence level)	21.8	6.3

Table 9. Orthophotography Data Accuracy Results at Pueblo PBR #2.

Accuracy Metrics	Phase I Data (cm)	Phase II Data (cm)
Y RMSE	13.1	9.9
Y linear error (95% confidence level)	25.7	19.5
X RMSE	10.3	12.0
X linear error (95% confidence level)	20.2	23.5
RMSE horizontal radial error (68.3% confidence level)	28.6	26.8
Horizontal radial error (95% confidence level)	56.2	52.6

4.1.2.2 Borrego

For the Borrego Military Wash demonstration, the LiDAR and orthophotography spatial accuracy performance goals were not met due to the restrictions on the emplacement of aerial targets. This restriction precluded the use of a standardized evaluation method for determining spatial accuracy of the datasets; instead, the georeference accuracy of both the orthophoto and LiDAR datasets depended entirely upon the airborne GPS/POS georeferenced data. The rake stations were used to calculate spatial accuracy as the eight corners of the two rake stations were clearly delineated in the processed datasets. To use the rake stations for this assessment, the rake station locations were defined in the field by real-time kinematic GPS (RTK GPS); the shape of each rake station feature digitized using the hillshade LiDAR image; and the offset between the two calculated. The measured offsets for the eight corners were then averaged to report the estimated accuracies. It should be noted that these estimates do not have measures of variance that provide meaningful information about the confidence error of the estimate since they are associated with a very limited number and scope of measures. This methodology was used to calculate the mean horizontal offset (89 cm) and the average horizontal offset (22 cm) in the LiDAR dataset and the average horizontal spatial offset (92 cm) of the orthophotography dataset (Table 10).

Table 10. LiDAR and Orthophotography Data Accuracy Results at Borrego.

Dataset	Accuracy Metrics	Results (in cm)
LiDAR	RMSE vertical linear error (68.3% confidence level)	62
LiDAR	Vertical linear error (95% confidence level)	22
LiDAR	Horizontal accuracy estimate	89
Orthophotography	Horizontal accuracy estimate	92

4.1.3 Target Area Detection

4.1.3.1 <u>Pueblo PBR #2</u>

Target features anticipated to be present based on historical data included target circles at bombing BT3 and BT4 observed in the 1951 aerial photography. The 1995 ASR field inspections located the aiming circle at BT3 but did not observe other target features (other potential HE craters). The 1995 ASR mentions the construction of an air-to-ground pattern gunnery range, conversion of five of the nine precision bombing targets to E-1 sonic bomb scoring targets, and the construction of skip bombing (ship) and submarine targets several years after the range was initially put into operation. Locations for these upgraded targets were not documented. Target features were identified at BT3 and BT4 using LiDAR, orthophotography, and hyperspectral imaging (HSI) data (Sky Research, 2007b). No munitions-related features were detected in the vicinity of the suspected 75-mm air-to-ground target in either the orthophotography or the LiDAR imagery.

At BT3, the following were detected—an aiming circle, inner concentric circles, a raised area within the aiming circle to the east, and a fenced area extending outside the aiming circle to the west (Figure 4). No crosshair features were mapped, even though some evidence for northern and western crosshair arms is suggested in the data. A possible ship target was partially detected west of the aiming circle. An area north of the aiming circle, approximately 100 m x 100 m, was identified as being a possible feature of interest related to BT3; this feature is comprised of raised areas indicative of potential berm-like features.

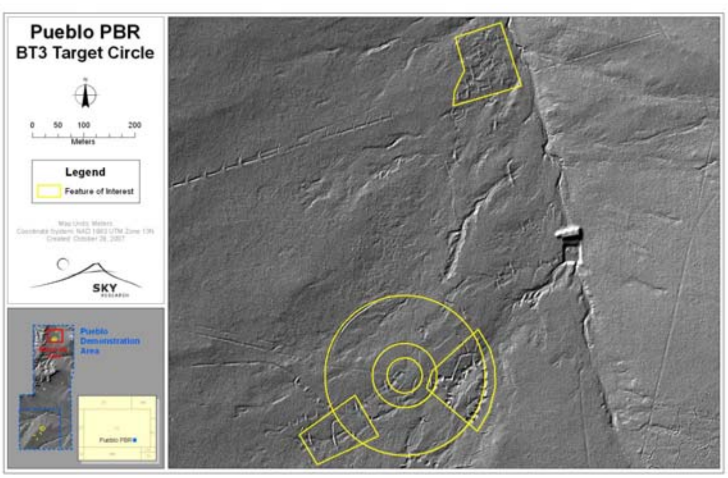

Figure 4. Delineation of Target Features at BT3 and Vicinity.

In the documented BT4 area, an aiming circle 1,000 foot in diameter was mapped; the aiming circle was intersected by a four-armed crosshair oriented NS-EW, each arm extending from the inner 200-ft circle to about 100-ft past the outer circle. Four ship targets ranging in length from about 160 to 210 m were mapped in the vicinity of BT4 (Figure 5). These features were constructed by grading raised berms in the shape of ship outlines, representing in approximate size and shape a World War II-era Japanese or German battleship. It is postulated that these target features at least partially account for the skip targets described in the ASR. These features are also best defined in the analytic high-pass LiDAR image. One ship target (immediately south-southwest of the BT4 circle) was observable in the HSI false-color minimum noise fraction (MNF) and high-pass LiDAR DEM imagery, but not in the orthophotography or hillshade images analyzed in the work.

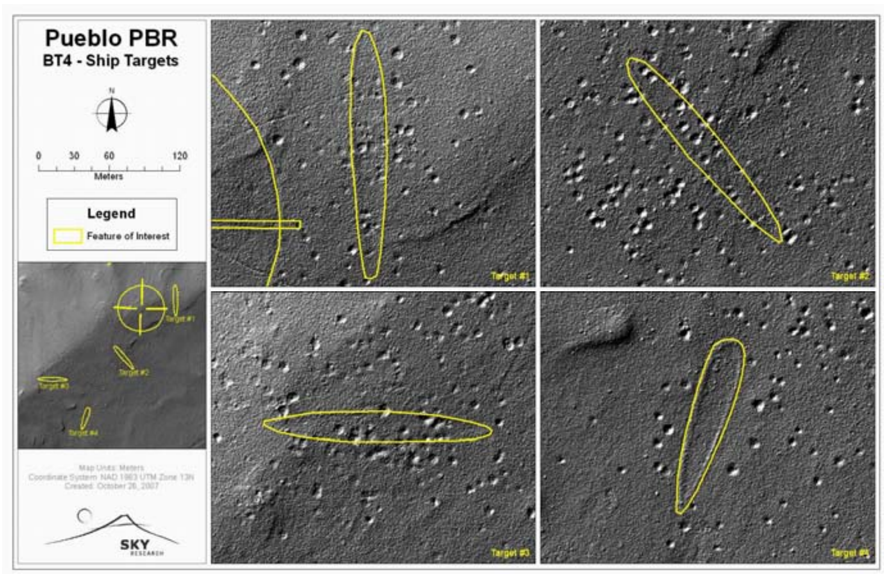

Figure 5. Four Ship Targets (Yellow Outlines) **Were Detected in the LiDAR Imagery in the Vicinity of BT4 at Pueblo PBR #2.** (A number of craters can be seen in the imagery surrounding the ship targets.)

4.1.3.2 <u>Borrego</u>

The results of the target feature analysis for the Borrego demonstration included a determination of the exact size and location of the Bomb Target 64 (BT64) target circles, a vehicle target and railroad strafing targets. In addition, there is evidence to support the conclusion that the rake stations were also used as targets; therefore, they are included as targets that were detected in the data.

The target circles for BT64 were located in a minor topographic basin lying in an upland dividing the main branches of the Borrego Military Wash that bisects the study area and approximately 1,000 ft to the east-southeast of the “target center” location point provided in the ASR. The BT64 target feature consisted of three concentric circles approximately 75 ft, 150 ft, and 300 ft in diameter (Figure 6).

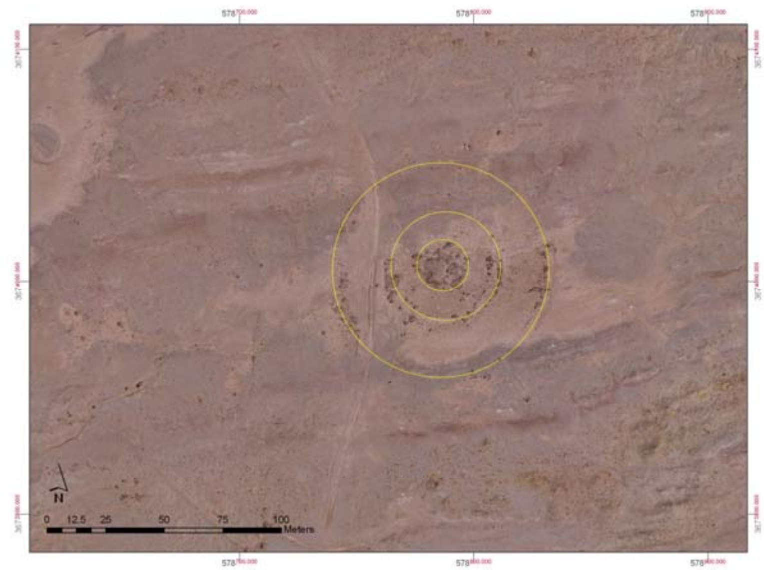

Figure 6. Extracted Circular Aiming Point Target Features for BT64 at Borrego Shown on Color Orthophoto.

These features were best defined in the orthophotography from the vegetation pattern that has emerged on the small ridges and can also be discriminated in the LiDAR analytic image.

The railroad strafing target (Figure 7) was located approximately 2,000 ft to the southeast of the "mile long wooden track" location point provided in the ASR in the same topographic basin where BT64 is located. This feature, a raised berm less than 0.5-m high and about 2,500 ft long (about 0.5 mile), runs east to west and was constructed by grading a raised berm in the configuration of a typical railroad bed. It was well defined in the orthophotography, LiDAR hillshade, and analytic high-pass LiDAR images. Ground support field observations at this location included burned fragments of milled wood and very high densities of box nails consistent with the ASR information.

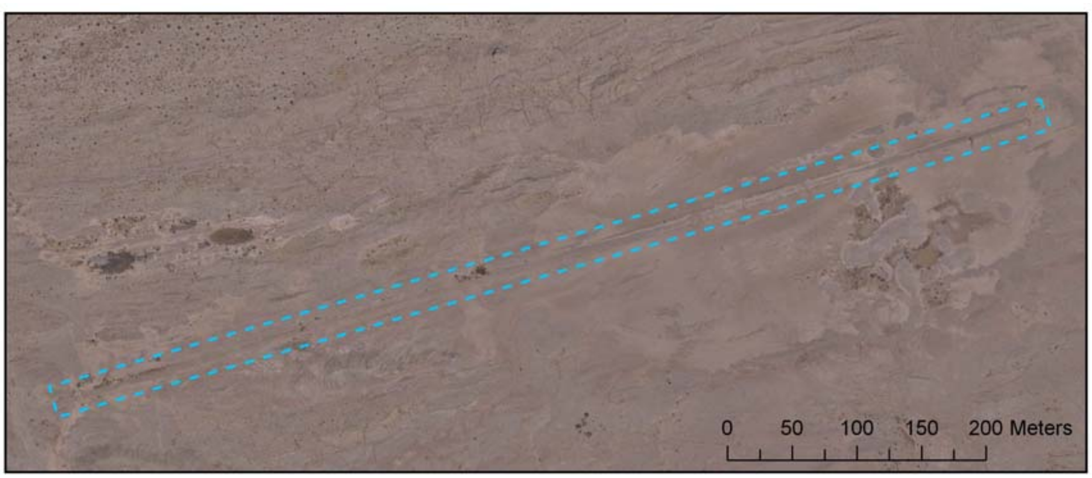

Figure 7. Extracted Railroad Strafing Target at Borrego Shown on the Color Orthophoto.

4.1.4 Crater Detection

4.1.4.1 <u>Pueblo PBR #2</u>

A total of 1,103 potential crater features were mapped on the combined Phase I and Phase II study areas; sixteen in the vicinity of BT3 and more than 1,000 in the vicinity of BT4. No HE cratering was evident in the suspected 75-mm air-to-ground target vicinity.

4.1.4.2 <u>Borrego</u>

No HE craters were detected in the vicinity of BT64 or elsewhere in the demonstration area. This result was not surprising since no HE aerial bombs had been documented in use at the site, and the only documented HE munitions were 5-in-high velocity air rockets (HVAR) that normally carried a relatively small (7 pounds of trinitrotoluene [TNT]) HE charge.

4.1.5 Range Infrastructure Detection

4.1.5.1 <u>Pueblo PBR #2</u>

Potential range infrastructure features detected in the LiDAR and orthophotography imagery included transportation routes, structures, and raised features.

4.1.5.2 <u>Borrego</u>

Two rake stations and a small depression were identified during data analysis. Positions for both rake stations were determined from the orthophoto imagery. The western rake station was located approximately 400 m northeast of the location provided in the ASR, and the eastern rake station approximately 330 m northwest of the ASR location. Both locations are situated on high ground looking northwards down into the area where BT64 and the railroad strafing target are located, and each has a clear view of both target features. Transport features mapped include the access road through the site that is currently in active use by park visitors. This road accesses both the eastern rake station and BT64. A small depression was also identified in the data analysis.

4.1.6 Site Characterization Results

4.1.6.1 <u>Pueblo PBR #2</u>

The results of the LiDAR and orthophotography data analyses established the precise location and extent of the two historically known bombing targets within the study area (BT3 and BT4), and provide no evidence that a suspected 75-mm target is located within the WAA study area. The clear detection of the two historically known bombing targets, and the conclusive detection of ship-shaped skip bombing targets mentioned but not located in the historical record, provide evidence that no undocumented similar targets exist within the study area. While the possibility for isolated munitions anywhere in and around the study area cannot be eliminated, the high-certainty elimination of the majority of the study area as potential bombing target impact zone provides significant efficiencies for subsequent survey activities.

4.1.6.2 Borrego

The high airborne datasets confirmed the presence of several known target features within the Borrego Wash WAA study area. However, one target circle that was identified from the ground was not detected in the orthophotography or LiDAR datasets due to weathering conditions at the site. No other features indicating concentrated munitions use were evident in other portions of the study area, although it is unknown whether additional features have been obscured by fluvial erosion processes or blowing sand. Therefore, due to less stable site conditions than at Pueblo, the reduction of munitions potential in non-target parts of the study area is significantly less certain.

4.2 PERFORMANCE CRITERIA

Table 11 identifies the expected performance criteria for these evaluations, complete with post-demonstration performance results (quantitative) and/or definitions and descriptions (qualitative). Performance confirmation methods included assessment of the use of LiDAR and orthophotography in a high airborne, fixed-wing aircraft; calculation of the georeference accuracies; and comparison of the feature detection results to the validation data.

4.3 DATA ASSESSMENT

The use of LiDAR and orthophotography in a high airborne, fixed-wing aircraft is an efficient means for collecting data over large survey areas. The LiDAR sensor and digital camera utilized for this demonstration are easy to operate, although they do require a skilled operator. Health and safety requirements for the operation of this technology are the same as for any flight operations. The standardized data processing and analysis methodologies are well understood and easy to use for experienced remote sensing analysts.

Georeference accuracies as specified in the demonstration design are more than sufficient for the accuracy needed to delineate features for further investigation. For PBR #2, demonstration met the expected georeference accuracies; the BMA demonstration did not. However, even though the georeference accuracies were not met, the ground survey team was still able to relocate the features detected in the data with sufficient accuracy to verify their locations.

Target features, craters, and range infrastructure features were found to be largely detectable in the data. The validation data for the PBR #2 data confirmed the identification and location of BT3 and BT4 and did not find evidence of contamination in the suspected 75-mm air-to-ground target area, confirming the findings of the LiDAR and orthophotography analysis. Regarding the detection of craters, the performance criteria originally developed for the performance assessment were as follows: 70% of craters less than 1 m in diameter were expected to be detected and 90% of potential craters greater than 1 m in diameter were expected to be detected. However, during the crater analysis conducted as part of this project, the results indicated that crater-like features smaller than 1 m in diameter were not detectable in LiDAR imagery. A complete discussion of crater detection performance can be found in the final technical demonstration report (Sky Research, 2008). Section 4.5.4 of the Pueblo demonstration report describes how the validation surveys determined the locations for 28 ground-observed circular

Table 11. Performance Confirmation Methods and Results.

Type of Performance Objective	Primary Performance Metric	Expected Performance (Metric)	Performance Confirmation Method	Observed Performance
Qualitative (Primary)	Ease of use and efficiency of operations	Efficiency and ease of use meets design specifications	General observations	Pueblo PBR #2: Pass
				Borrego: Pass
Quantitative (Primary)	Georeference position accuracy for each sensor system	LiDAR: Vertical accuracy – 15-cm RMSE; Horizontal accuracy – 40-cm RMSE	Pueblo PBR #2: Comparison of data sets with ground fiducials Borrego: Calculated from average offset for eight corners of two rake stations*	Pueblo PBR #2: Vertical accuracy: Phase I: 11.1 cm Phase II: 3.2 cm Horizontal accuracy: Phase I: 28.2 cm Phase II: 8.5 cm
				Borrego: Vertical accuracy: 62 cm (22 cm relative to adjacent sample points); estimated horizontal accuracy of 89 cm
		Orthophotography: Horizontal accuracy – 40-cm RMSE	Pueblo PBR #2: Comparison of data sets with ground fiducials Borrego: Calculated from average offset for eight corners of two rake stations*	Pueblo PBR #2: Phase I: 28.6 cm Phase II: 26.8 cm
				Borrego: 92-cm RMSE

26

Table 11. Performance Confirmation Methods and Results (continued).

Type of Performance Objective	Primary Performance Metric	Expected Performance (Metric)	Performance Confirmation Method	Observed Performance
Quantitative (Primary)	Target area detection	>0.90 of target areas having topographic aiming point features	Comparison of ortho and LiDAR data analysis results with ground validation data**	Pueblo PBR #2: BT3 and BT4 detected. No target features detected at the suspected 75-mm air-to-ground target area, which was confirmed by absence of target evidence during validation surveys.
				Borrego: 0.83 five target features detected (target circle, railroad strafing target, two rake stations, and small depression); one target feature (circle) not detected
Quantitative (Secondary)	Crater detection	>0.75 (craters <1 m) >0.90 (craters >1 m)	Comparison of LiDAR data analysis results with ground validation data**	Pueblo PBR #2: <1 m: Not within detection limits >1 m: Performance met Borrego: No craters detected
	Range infrastructure detection	>0.90	Comparison of ortho and LiDAR data analysis results with ground validation data**	Pueblo PBR #2: N/A*** Borrego: Identified features verified as range infrastructure

* Performance confirmation method reported is typically comparison of datasets with ground fiducials; however, for the Borrego demonstration, another confirmation method (as described in Section 4.1.2.2) was used because of restriction on emplacements of fiducials, which also resulted in a lower accuracy than anticipated.
** For the Borrego demonstration, visual site inspection results were utilized for validation purposes.
*** The range infrastructure visited during the validation survey was not sufficient to calculate a meaningful detection estimate; therefore, no value was reported for this criterion.

27

depressions identified as potential detonation craters, of which 27 were detected in the analysis. Based on this sample, it was estimated that the 90% detection goal had been achieved. Last, potential range infrastructure features were detected in the imagery, but it was determined that range infrastructure needs to be reviewed in the context of the current land use.

The Borrego site presented a number of interesting new challenges to WAA technologies and methods based on a foundation of high resolution LiDAR and orthophoto datasets. First, environmental considerations required that ground-disturbing fiducials and aerial targets not be used led to a reduction in geospatial data accuracy. Second, the part of the study area containing the main target features was subject to water erosion and periodic flooding and wind erosion and deposition, with significant reduction in the ability to observe features. As a result, the demonstration did not meet the performance objective of target feature detection because one feature out of a total of six possible features was not detected. This feature, a second target circle, was defined by widely spaced scattered rock piles aligned in a circular pattern that were too small to be delineated from the underlying terrain in either the LiDAR or the orthophoto datasets. The Borrego site was selected because the erosional and depositional conditions of blowing sand and periodic flooding represent significant challenges to Munitions Related Feature (MRF) detection; it is clear from the analysis that while MRFs could be detected at Borrego, false negatives are possible in this kind of environment.

In addition to natural disturbance such as the conditions encountered at Borrego, the persistence of munitions-related features on a site can be impacted by human activities. At PBR #2, the lack of crater features within the BT4 aiming circle boundaries led to the presumption that clearance and grading occurred sometime after HE bombs were dropped. However, the target area was still identifiable due to the extensive cratering still present surrounding the BT4 aiming circle and adjacent ship targets.

Other limitations to the use of LiDAR and orthophotography technologies included delays due to inclement weather during the PBR #2 Phase I demonstration.

4.4 TECHNOLOGY COMPARISON

The WAA pilot program utilized numerous sensor technologies and deployment platforms in a layered approach, from high altitude to ground-based systems, to explore how various combinations of technologies might be useful in efficiently characterizing potential munitions contamination and supporting site decisions regarding remediation activities.

High-altitude LiDAR and orthophotography provide rapid survey coverage over large areas and assist in the identification of munitions-related features. This rapid, big-picture assessment provides important information for defining the location and extent of munitions use areas within a site, and provides support for decisions about how to allocate more detailed and costly survey efforts across the entire site.

The other WAA technologies employed in the pilot program, helicopter-based magnetometry and ground-based geophysics, are used to detect the density and extent of surface and subsurface ferromagnetic materials and individual munitions items, respectively. In comparison with high airborne sensors, these technologies provide more detail regarding the location and abundance of metallic munitions and artifacts but less information about the patterns of vegetation and terrain disturbance that reveal past munitions-related land uses and at less efficient coverage rates and cost per acre. Therefore, comparisons between the various WAA sensor technologies generally indicate complimentary roles in the overall WAA process, although some promising technologies such as airborne imaging spectrography and synthetic aperture radar require further development.

A technology comparison with current practices that do not incorporate WAA remote sensing guidance in munitions site remediation, such as standard full-coverage mag-and-flag ground operations, highlights the value of the WAA process. The orthophotography and LiDAR datasets and analysis provide significant efficiencies to subsequent munitions recovery operations by locating and characterizing major contamination features such as bombing targets, firing ranges, and other features. The detailed terrain and land cover information generated also represents important operational planning aids for ongoing recovery activities.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

Cost information associated with the demonstration of all airborne technology, as well as associated activities, were tracked and documented before, during, and after the demonstrations to provide a basis for determining the operational costs associated with this technology. Tables 12 -14 contain the cost elements that were tracked and documented for this demonstration. These costs include both operational and capital costs associated with the demonstration design and planning; salary and travel costs for support staff; equipment costs associated with aircraft, sensor, and camera; support personnel; and costs associated with the processing, analysis, and interpretation of the results generated by this demonstration.

5.2 COST ANALYSIS

The cost of an airborne survey depends on many factors, including:

- Aircraft costs. The rental rate for aircraft will be influenced in part by the type of aircraft utilized and the cost of fuel (if included in the cost of the aircraft time). In addition, standby time, if needed, will increase the survey costs.
- Length and number of flight lines required to survey the demonstration area.
- Accuracy requirements, which influence the speed and altitude of the survey flights and the amount of data processing required.
- Location of the site, which can influence the cost of mobilization and logistics.
- Amount of analysis required to sufficiently review the data.

Costs associated with the pre-survey calibration flights were not included in either demonstration. Costs associated with the ground validation surveys to collect post-survey data were not considered in the cost analysis, as the validation was conducted as part of the WAA pilot program. Last, this demonstration was one of several concurrent demonstrations conducted by Sky Research for the WAA pilot program. Some of the costs associated with management were shared among demonstrations, lowering the costs incurred for this demonstration.

Aircraft costs are a major cost factor for any airborne survey. Significant variables and factors associated with the mobilization, data acquisition, and demobilization costs include the cost of aircraft time and standby time. The cost of aircraft can vary depending on the type of aircraft and operating costs. Standby time can also influence the cost of a survey and is typically assessed at the cost of one day of data collection, including aircraft costs, labor, and travel. For the Pueblo PBR #2 demonstration, two standby days were called during the Phase I demonstration due to weather. The standby time for the aircraft during this demonstration was four hours of aircraft cost per standby day.

Table 12. Pueblo PBR #2 Phase I Cost Tracking.[1]

Cost Category	Subcategory	Details	Costs ($)
Start-up costs	Pre-Deployment and Planning: Includes planning, contracting, pre-survey site visit	Labor: Contracting	$2,172
		Labor: Site visit	3,646
		Labor: Planning	655
		Site visit travel	1,840
		Materials and supplies	$96
		Subtotal: predeployment planning	**$8,409**
	Mobilization: Personnel mobilization, equipment mobilization and transportation	Aircraft time (4.5 hours)	$5,711
		Equipment	0
		Labor	1,154
		Travel	1,065
		Subtotal: mobilization	**$7,930**
		Total start-up costs	**$16,339**
Operating costs	High Airborne Survey: Data acquisition and associated tasks, including aircraft operation time	Aircraft time (5.2 hours)	$6,600
		Aircraft standby time (8 hours)	10,153
		LiDAR sensor	1,226
		Digital camera	491
		GPS equipment	218
		Labor	2,523
		Travel	1,251
		Materials and supplies	165
		Total operating costs	**$22,627**
Demobilization	Demobilization: Personnel demobilization, equipment demobilization Personnel demobilization, equipment demobilization and transportation	Aircraft time (4.5 hours)	$5,711
		Equipment	0
		Labor	1,154
		Total demobilization costs	**$6,865**
Data processing	Data processing	Labor	25,238
Data analysis	Data analysis	Labor	26,045
Management	Management and reporting	Project related management, reporting and travel	30,462
		Subtotal	**$81,745**
		Total Costs	**$127,576**
		Acres Surveyed	**6,700**
		Unit Cost	**$19.04/acre**

[1] All costs reported for the demonstration include overhead and organization burden and fees.

Table 13. Pueblo PBR #2 Phase II Cost Tracking.[2]

Cost Category	Subcategory	Details	Costs ($)
Start-up costs	Predeployment and planning: Includes planning, contracting, pre-survey site visit	Labor: Contracting	$300
		Labor: Site visit	5,653
		Labor: Planning	2,351
		Site visit travel	3,940
		Materials and supplies	198
		Subtotal: predeployment planning	**$12,442**
	Mobilization: Personnel mobilization, equipment mobilization and transportation	Aircraft time (4.5 hours)	$5,711
		Equipment (4 days of GPS equipment)	3,443
		Labor	7,788
		Travel	5,946
		Subtotal: mobilization	**$22,888**
		Total start-up costs	**$35,330**
Operating costs	High airborne survey: Data acquisition and associated tasks, including aircraft operation time	Aircraft time (4.2 hours)	$5,341
		LiDAR sensor	6,208
		Digital camera	3,679
		GPS equipment	2,148
		Labor	2,622
		Travel	3,239
		Materials and supplies	3,213
		Total operating costs	**$26,450**
Demobilization	Demobilization: Personnel demobilization, equipment demobilization Personnel demobilization, equipment demobilization and transportation	Aircraft time (4.5 hours)	$5,711
		Equipment (3 days of GPS equipment)	2,582
		Labor	2,169
		Travel	3,291
		Total demobilization costs	**$13,753**
Data processing	Data processing	Labor	21,417
Data analysis	Data analysis	Labor	8,407
Management	Management and reporting	Project related management, reporting and travel	29,137
		Total costs	**$134,494**
		Acres surveyed	**6,600**
		Unit cost	**$20.38/acre**

[2] All costs reported for the demonstration include overhead and organization burden and fees.

Table 14. Borrego Military Wash Cost Tracking.[3]

Cost Category	Subcategory	Details	Costs ($)
Start-up costs	Predeployment and planning: Includes planning, contracting, pre-survey site visit	Labor	$3,413
		Travel	2,133
		Subtotal: predeployment planning	**$5,546**
	Mobilization: Personnel mobilization, equipment mobilization and transportation	Aircraft time (4.2 hours)	$5,282
		Equipment	0
		Labor	2,667
		Travel	2,226
		Subtotal: mobilization	**$10,175**
		Total start-up costs	**$15,721**
Operating costs	High airborne survey: Data acquisition and associated tasks, including aircraft operation time	Aircraft time (3.6 hours)	$4,528
		LiDAR sensor	6,208
		Digital camera	1,738
		GPS equipment	384
		Labor	1,783
		Travel	1,867
		Materials/supplies/shipping	1,998
		Total operating costs	**$18,506**
Demobilization	Demobilization: Personnel demobilization, equipment demobilization and transportation	Aircraft time (3.4 hours)	$4,276
		Equipment	0
		Labor	813
		Travel	1,068
		Total demobilization	**$6,157**
Data processing and analysis	Data processing and analysis	Labor	$11,400
		Total data processing and analysis	**$11,400**
Management	Project related management, reporting and contracting	Labor	$14,834
		Total management	**$14,834**
		Total costs	**$66,618**
		Acres surveyed	**7,940**
		Unit cost	**$8.39/acre**

[3] All costs reported for the demonstration include overhead and organization burden and fees.

Mobilization and demobilization costs are most significantly a function of the distance from the home base for the aircraft. In addition to the cost of mobilizing and demobilizing the aircraft, the cost of mobilizing equipment (sensors and GPS equipment) can add significantly to costs. For these demonstrations, the daily rates for the LiDAR sensor and digital camera were not charged for mobilization and demobilization because each required less than one day. For a mobilization taking a full day or longer, the daily rate for the LiDAR sensor and digital camera would have been assessed, increasing the mobilization and demobilization costs. GPS equipment was mobilized from Denver, and the preparation and shipping time was charged for mobilization and demobilization. Therefore, for a site requiring a longer mobilization distance, the mobilization and demobilization can take up a correspondingly larger amount of the budget, especially when considered as a percentage of the cost for surveys of relatively small areas.

For the costs associated with the data acquisition flights, the predominant costs are the cost of the aircraft and equipment. The major driver for these costs is the survey size; secondarily, the shape of the survey areas can influence the costs. Fixed-wing aircraft can cover up to approximately 15,000 acres per day on average. Sites less than this in size will therefore be more expensive on a per acre basis. With respect to the shape of the survey boundaries, the demonstrations at Pueblo PBR #2 and Borrego were completed efficiently in part because the survey areas were regularly shaped, allowing efficient coverage with a minimum number of flight lines. Irregularly shaped survey areas or surveys with a number of noncontiguous parcels will increase the number of flight lines required for complete coverage, thereby increasing flight time and survey costs. The remainder of costs associated with data acquisition include labor, travel, and materials/supplies.

Data processing and analysis costs are generally linear with project size. For these demonstrations, data processing and analysis made up approximately 31% of the costs associated with the Pueblo PBR #2 demonstrations. The data processing and analysis functions for the Borrego demonstration made up approximately 17% of the demonstration cost; this is due in large part because no additional WAA data was collected for this site, which decreased analysis time. Last, the site conditions encountered at Pueblo PBR #2 and Borrego were benign for analyzing the data. Environmental conditions such as steep topography or vegetation can increase the amount of time needed for analysis in more challenging settings. An additional cost factor, processing and analysis, has been decreasing with experience at multiple sites, automation of processing and analysis routines, and increased computing power resulting in faster processing.

Project management and reporting were a somewhat significant cost for these demonstrations, as the projects were conducted under the WAA pilot program and required more meetings and reporting than would generally be expected for a production level survey.

5.3 TYPICAL AIRBORNE SURVEY COSTS

Mobilization distance, site size and shape, site conditions, and project objectives can influence the costs of data collection and analysis. In addition, this demonstration utilized a fixed-wing aircraft. Different kinds of fixed-wing aircraft will have somewhat different hourly rates than the rates used in this demonstration.

To generalize typical airborne survey costs, various scenarios are presented in Table 15 for several sizes of survey sites. For these scenarios, the following assumptions have been made: the site is generally amenable for the detection of surface features in remote sensing data and therefore will require an average amount of processing and analysis; the project objectives require accuracies similar to those used for these demonstrations; the mobilization distance is a 4-hour or less flight distance; and for a very small site (~1,000 acres), the ground support team will be one person traveling with the survey team.

Each scenario includes several categories of costs and tasks, including the following:

- Planning, Preparation and Management
  - Historical information review
  - Work plan development
  - Flight planning
  - Logistics planning
  - Ground control planning
  - Staff preparation and equipment review
  - Management including contracting, client interaction, etc.
- Mobilization/Demobilization
  - 4 hours of fixed-wing flight time each direction
  - Labor for pilot, co-pilot, sensor operator, ground survey team
  - 1 day of equipment costs (LiDAR sensor, camera, GPS equipment)
  - Travel costs
- Data Acquisition
  - Fixed-wing aircraft (minimum of 4 hours of flight time per day)
  - Materials and supplies for ground fiducials
  - Labor for pilot, co-pilot, sensor operator, ground survey team
  - Travel costs
- Data Processing, Analysis, and GIS Products
  - Data processing
  - Analysis
  - Quality control
  - GIS products, including maps (including online mapping for larger sites)
- Reporting/Documentation
  - Final report
  - Metadata development
  - Data compilation and delivery
  - Data archiving

Table 15. Estimated Costs Scenarios for LiDAR and Orthophotography.

Cost Category	1,000-Acre Site	10,000-Acre Site	50,000-Acre Site	250,000-Acre Site
Planning, Preparation, and Management	$10,000	$16,000	$24,000	$31,000
Mobilization/Demobilization	15,000	31,000	32,000	39,000
Data Acquisition	30,000	60,000	89,000	251,000
Data Processing, Analysis, and GIS Products	12,000	22,000	49,000	178,000
Reporting and Documentation	2,000	5,000	10,000	20,000
Total costs	**$69,000**	**$134,000**	**$204,000**	**$519,000**
Costs per acre	**$69.00**	**$13.40**	**$4.08**	**$2.08**

As discussed, additional costs would be assumed for a greater mobilization distance; each additional hour of flight time would increase the mobilization/demobilization costs by approximately 10%. Data acquisition costs could decrease if the required accuracies are less than those used for these demonstrations, as the flight survey speeds could increase. Data processing and analysis costs could also decrease from the estimates provided if less extensive data analysis and feature selection is required. The deliverable products include reports, maps, GIS data layers, and in some cases, an online, interactive mapping site that allows stakeholders access to spatial data for viewing, exploring, analysis, and display. In terms of basic data products, these cost estimates include full LiDAR point clouds in Log ASCII Standard (LAS) or ASCII format, surface and bare earth DEMs, high-resolution orthophotography (both image tiles and geodatabase mosaics), and all feature extractions in vector feature classes in a GIS geodatabase. All data collection, processing, calibration, and accuracy reporting is also included. The estimates above assume that for the 10,000+ acre sites, an online mapping site will be created to support client interaction. The costs for the GIS products may be somewhat lower without online mapping. Last, the reporting for LiDAR and orthophotography projects may vary according to the requirements of the client.

5.4 COST CONCLUSIONS

A number of factors should be considered for DoD-wide application of WAA, including the acquisition of LiDAR and orthophotography data, when evaluating the appropriateness of the airborne technologies and potential for cost savings. Sites must be large enough to justify the deployment of aircraft and equipment to conduct a survey. Climatic conditions and terrain can limit the results of surveys. Time of year should also be taken into account with respect to sun angles, leaf-off, and likelihood of snow (obscuring the earth's surface) or other weather impediments. However, in amenable sites, the use of LiDAR and orthophotography to focus subsequent helicopter magnetometry and ground surveys can provide substantial cost savings.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The costs as reported and analyzed are for the concurrent collection of orthophotography and LiDAR data. Remote sensing analysts utilized the LiDAR data more extensively for detection of munitions-related features; orthophotography was used to cross-reference and verify some of the features detected. However, a few features were better defined in the orthophotography. Because the two data sets can be collected concurrently, the cost to acquire orthophotography with LiDAR data does not significantly add to the overall cost. The costs associated with processing orthophotography data are on the order of 25% of the total data processing budget. The usefulness of orthophotography in corroborating visual analyses of LiDAR data supports the recommendation that these data sets together provide the greatest benefit for WAA.

Overall, these sites were amenable to cost-effective collection of high-altitude data: they had relatively short mobilization distances; they were open areas; and the demonstration boundaries provided an aerial footprint for the efficient collection of data. For these demonstrations, the sites were relatively small for the use of these technologies (i.e., under 10,000 acres, requiring less than a full day for data collection). The costs associated with larger surveys will be less, although mobilization costs may be greater if the mobilization distance is greater.

Sky Research has been able to reduce some of the costs associated with collecting, processing, and analyzing LiDAR and orthophotography data by incorporating recent lessons learned from subsequent munitions response-related projects. For example, as project organization activities have become more standardized and efficient there has been a reduction in the amount of time required in planning large scale surveys. The addition of supplementary computing resources (both hardware and software) in 2006 and the development of standard processing models and algorithms have led to an increase in automation and a decrease in the amount of time and labor required to process large data sets. Lastly, since the Phase I data collection at Pueblo in 2004, there have been improvements in sensor technologies yielding increased efficiency; advances in these technologies will likely continue to lower the costs associated with their use.

6.2 PERFORMANCE OBSERVATIONS

The performance objectives were largely met by this demonstration. The georeference accuracies for both data sets were higher than expected for the Pueblo demonstration. Feature detection for the Pueblo demonstration met the expected performance. Target circles, ship targets, craters, and range features were all detectable in the imagery. The validation data confirmed the identification and location of BT3 and BT4 and did not find evidence of a target area in the suspected 75-mm air-to-ground target area, confirming the findings of the LiDAR and orthophotography analysis.

Borrego presented a more challenging site because site restrictions and climatic conditions obscured some features and one of the two target areas was not detected. Therefore, it is important to review and assess the site characteristics and the potential impact these conditions might have on the results before undertaking a WAA.

6.3 SCALE-UP

There are no scale-up issues with this technology; LiDAR and orthophotography can be utilized as demonstrated to characterize a large number of sites. However, their use on very small sites may not be cost effective; the larger the site, the more cost effective their use on a per acre basis.

6.4 OTHER SIGNIFICANT OBSERVATIONS

The two sites illustrate the difference site conditions can have on results. The Pueblo site was a good candidate for the use of high-altitude remote sensing technologies for site characterization as surface features persisted and were detectable in both the LiDAR and orthophotography imagery. The Borrego site qualifies the generalization that arid desert and high plains munitions sites are uniformly well preserved from natural disturbance and amenable to remote sensing feature detection methods. Soils, hydrology, climate, and human disturbance factors need to be carefully considered for each prospective WAA site in order to understand the probable persistence of features over time and the likelihood of detection for various types of munitions-related features.

6.5 LESSONS LEARNED

The primary benefit of these high-altitude technologies are the rapid characterization of large open areas. Cost analysis shows that, in general, costs per acre decrease with the increase in size of the project area. However, complex sites (e.g., densely vegetated or topographically steep and variable landscapes) requiring extended labor in data processing and analyses, or complicated data collection surveys (due to inclement weather, climatic conditions, logistical difficulties, etc.) can increase the per unit costs.

6.6 END USER ISSUES

Implementing WAA for production-level surveys should include end users in the project. For this project, ESTCP utilized the WAA Advisory Group to understand and evaluate potential end user issues and concerns that can impact the widespread implementation of WAA technologies. End users should also be provided online access to WAA data and analytical tools through the use of GIS, as demonstrated in the WAA GIS demonstration (MM-0537). Last, the DEM and orthophotography datasets can be utilized for site planning across the entire site for a variety of purposes and should be provided to end users.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The ESTCP Program Office established an Advisory Group to facilitate interactions with the regulatory community and potential end users of this technology. Members of the Advisory Group included representatives of the USEPA, State regulators, USACE officials, and representatives from the services. ESTCP staff worked with the Advisory Group to define goals for the WAA pilot program and develop Project Quality Objectives.

A number of issues will need to be overcome to allow widespread implementation of WAA beyond the pilot program. Most central is the change in mindset that will be required if the goals of WAA extend from delineating target areas to collecting data that are useful in making decisions about areas where there is not indication of munitions use. Therefore, the challenge for adoption of a WAA approach with respect to regulatory acceptance may be collecting sufficient data, evaluating the applicability of these technologies to uncontaminated land, and understanding the results. Similarly, demonstrating that WAA data can be used to provide information on target areas regarding boundaries, density and types of munitions to be used for prioritization, cost estimation, and planning will require that the error and uncertainties in these parameters are well understood.

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APPENDIX A

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